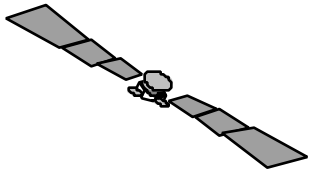

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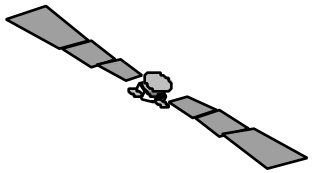
Spacecraft Arcing: What Flight Experiments Have Told Us

Dr. Dale C. Ferguson
NASA Lewis Research Center



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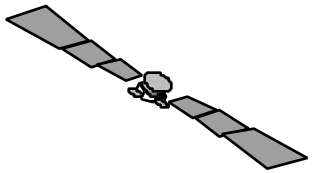
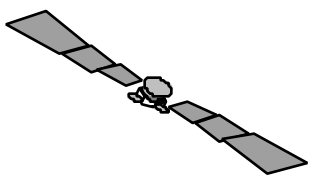
1. Arcs can happen at conductor-insulator junctions whenever a strong electric field exists on the insulator (LEO or GEO)
2. Arcs can happen where thin dielectrics cover conductors whenever a strong electric field exists within the dielectric
3. Arcs can happen whenever a locally high neutral pressure supports Paschen discharge
4. When an arc occurs, a locally high density plasma is created, which can support current through a plasma circuit
5. If sufficient current and voltage can continue to be supplied to a plasma circuit, arcs can become continuous and highly damaging



❶ Arcs can happen at conductor-insulator junctions whenever a strong electric field exists on the insulator (LEO or GEO)

- **PIX-II (1983) showed that the LEO plasma can induce arcs on solar arrays biased negatively relative to the space plasma, that a threshold voltage exists, and that the arc rate is a steep function of voltage above the threshold**
- **In the dense thermal LEO plasma, the strong electric field is set up between solar cell coverslips or substrate insulators (held at near plasma potential by the plasma) and interconnects or cell semiconductors which are highly negative because of the floating potential characteristics of high voltage arrays**
- **The electric field is stronger (and the voltage threshold lower) for more perfect insulators (highly resistive coverslips or substrates)**



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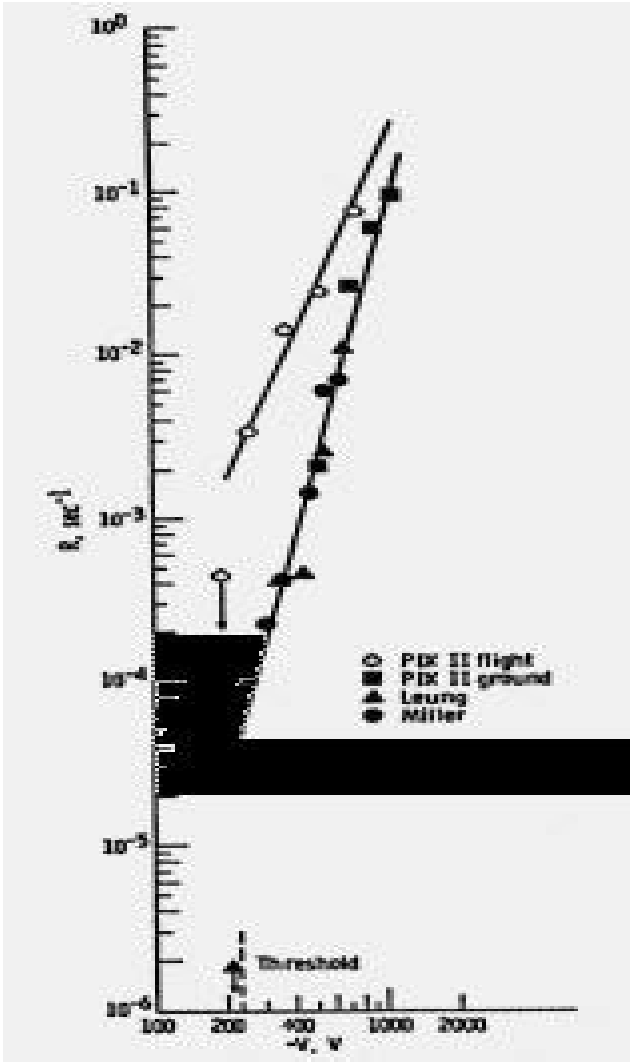
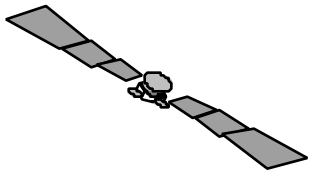
- Solar array LEO plasma ground test (Space Station cells) at NASA LeRC
- Engineer - Norm Grier (now retired)

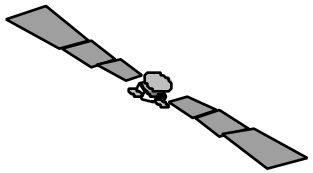


- Arc rates & thresholds for 2x4 cm silicon solar cells, with standard interconnects and normal glass and normal thickness coverslips at room temperature
- PIX-II and ground test data, normalized by flux density to normal LEO conditions



❶ **Arcs can happen at conductor-insulator junctions whenever a strong electric field exists on the insulator (LEO or GEO)**

- **SCATHA (1979) showed that arcing events could be produced at conductor-insulator junctions in GEO because of natural spacecraft charging.**
- **In the rarefied GEO plasma, charging of the spacecraft to potentials thousands of volts negative of the ambient plasma can occur due to high energy electron fluxes during solar substorms. The high electric field is then set up by partial discharging of coverslips or insulators by the photoelectric effect.**
- **The electric field is stronger (and the charging threshold lower) for more perfect insulators (highly resistive coverslips or substrates)**



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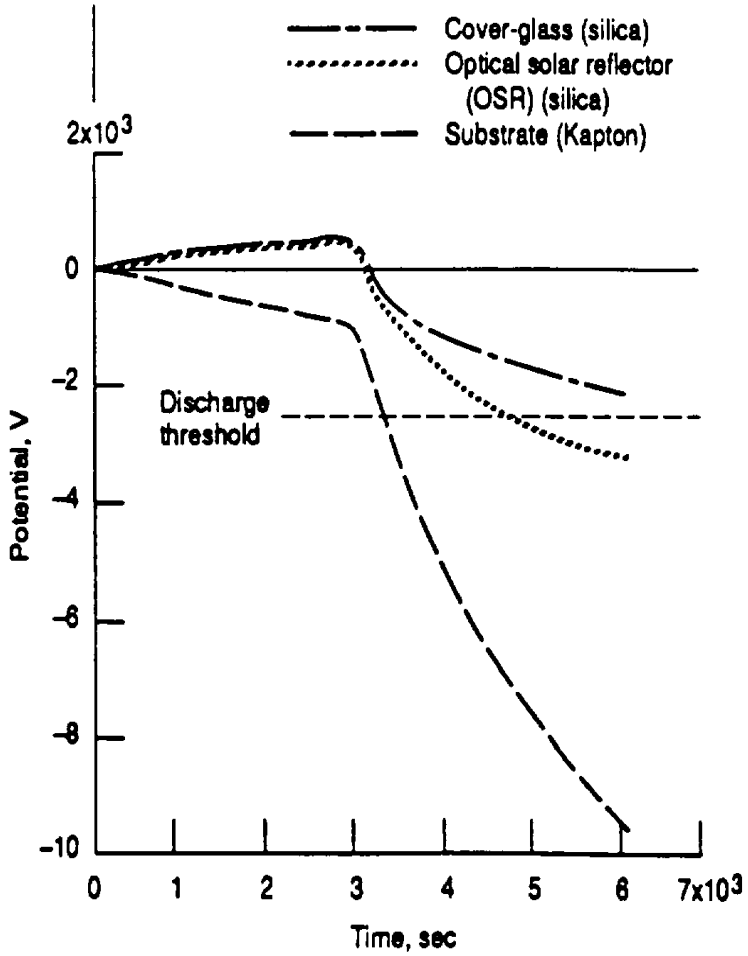
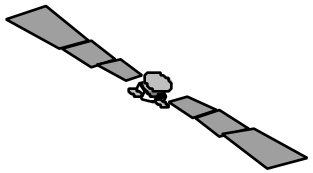
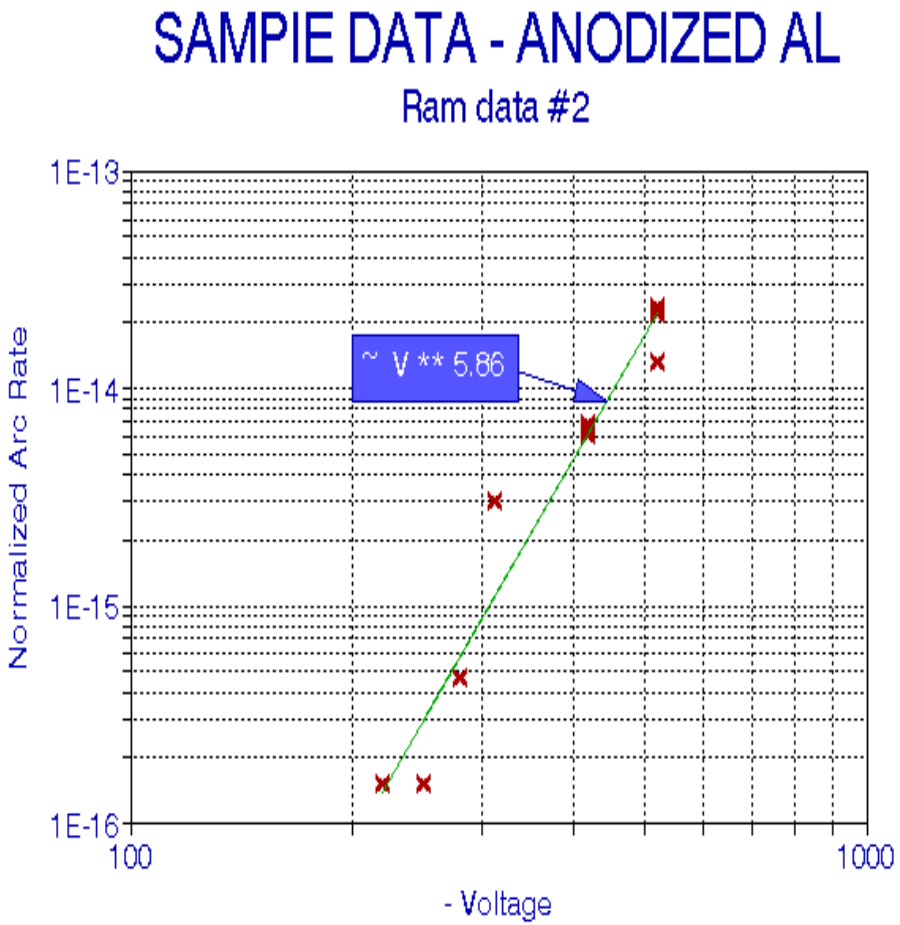


- NASCAP calculation of charging on GEO ACTS satellite in a geomagnetic substorm
- Differential charging may lead to arcing

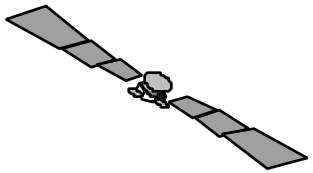


❷ Arcs can happen where thin dielectrics cover conductors whenever a strong electric field exists within the dielectric

- **SAMPIE (1994) showed that anodized aluminum surfaces can break down when the underlying metal is biased negative of the LEO plasma, that there is a voltage threshold, and that the arc rate is a steep function of the voltage above the threshold.**
- **In LEO, the high density ambient plasma keeps dielectric surfaces at the plasma potential, and the underlying metal may be at a high negative potential, because of the floating potential characteristics of negatively grounded high voltage solar arrays.**
- **The electric field is greater (and the voltage threshold lower) for thin dielectrics, and the breakdown field required is less (and the voltage threshold lower) for thin and/or porous dielectrics.**

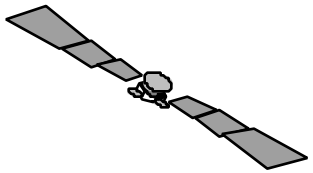


- Arc Rate vs Voltage - Anodized Aluminum, SAMPIE data
- Voltage threshold for this sample about - 220 V
- Rate varies as about 6th power of Voltage above threshold



❸ Arcs can happen whenever a locally high neutral pressure supports Paschen discharge

- **SAMPIE (1994) and TSS-1R (1996) showed that whenever local gas pressures and voltage differences get into the Paschen discharge regime, large, continuous arcs can occur.**
- **Local gas pressures can become large enough for Paschen breakdown due to outgassing into an enclosed space (SAMPIE's potting compound pulled loose from a high voltage component and outgassed into the created space) or from inadvertent gas flows into an enclosed space (TSS-1R's tether flowed gas into the reel enclosures).**
- **Voltage differences necessary for breakdown can be obtained from Paschen curves for the appropriate gases.**



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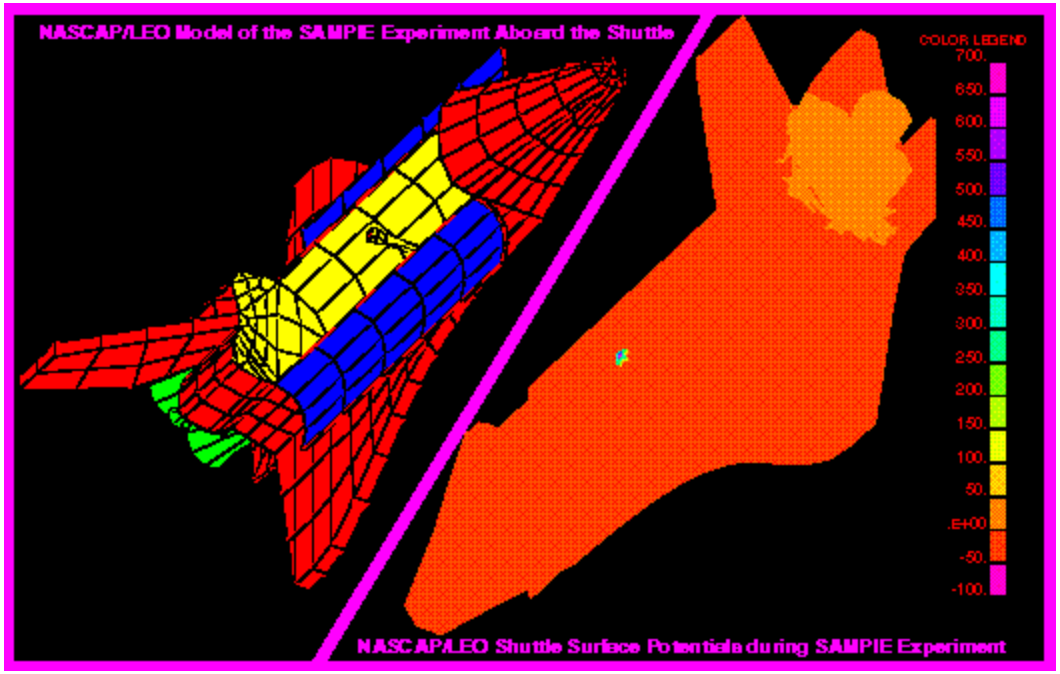
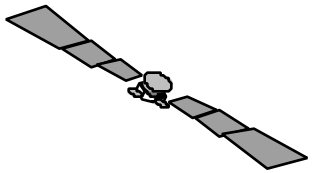
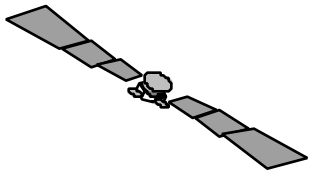


- SAMPIE and Shuttle floating potentials model (NASCAP/LEO)
- Similar calcs now easily done with EWB



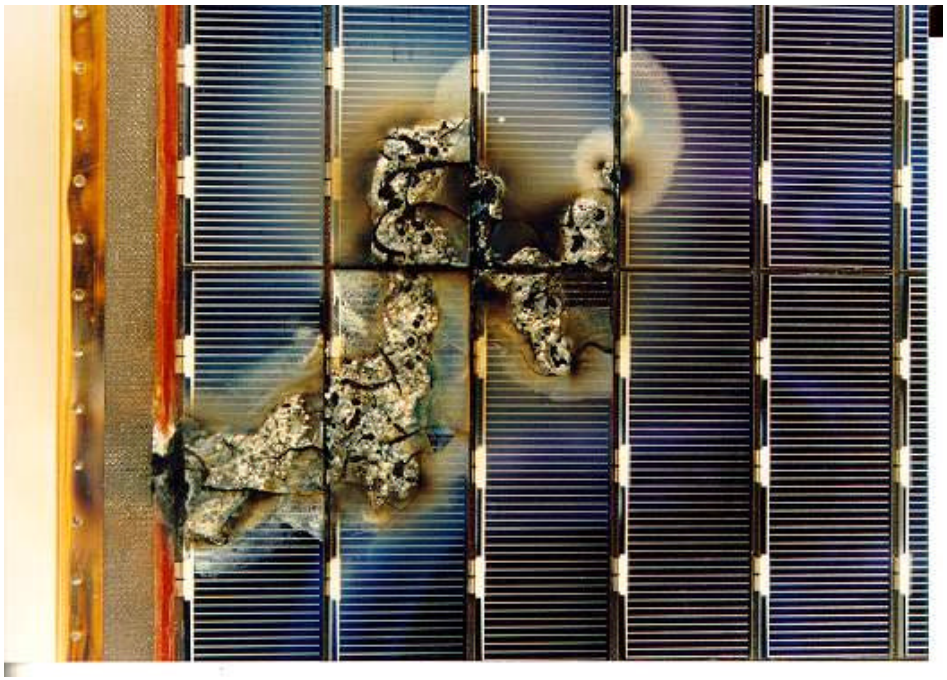
❹ **When an arc occurs, a locally high plasma density is created, which can support current through a plasma circuit**

- **Many examples in the Spacecraft Anomaly Database show that an arc-generated plasma can discharge the capacitance of GEO solar array coverslides, creating power surges (with accompanying EMI) or interrupting power for short times (microseconds).**
- **On TSS-1R (1996), current flowed between the tether and the Shuttle (and between Shuttle and the surrounding plasma) until the tether was no longer enclosed (for seconds).**
- **In Space System Loral's Tempo anomalies (1997), current flowed between adjacent cells which were at different voltages (for seconds to minutes).**
- **Loral's experience shows that current can flow through an existing arc plasma at relatively low voltage differences (60 V).**

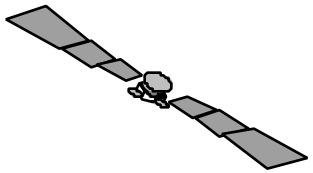


❺ If sufficient current and voltage can continue to be supplied to a plasma circuit, arcs can become continuous and highly damaging

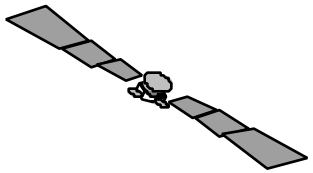
- **On TSS-1R (1996), current flowed between the tether and the space plasma for minutes after the tether was severed by the intense heat of the 1 amp arc. Here, the electron current was collected at the satellite end and returned at the severed end.**
- **After Space System Loral's Tempo anomalies (1997), ground tests showed that 1 amp currents flowed continuously between adjacent cells of 60 V difference until adjacent Kapton pyrolized, causing a permanent short.**
- **Thresholds probably exist for separation distance, voltage difference, and continuous current, but they may be extremely hardware (and temperature) dependent!**



- Eureca array returned from LEO by Shuttle
- Failure mechanism same as for Loral arrays in GEO
- Continuous arcing evident from charred Kapton, melted coverslips

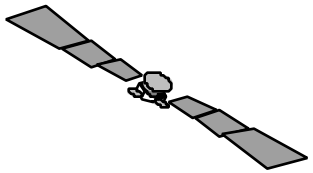


- Words of Warning!
  - » Theoretical thresholds are not reliable - they must be tested for.
  - » Thresholds vary for different materials and geometries.
  - » Thresholds on the voltage difference of adjacent conductors for continuous arcing may be smaller than the voltage threshold for initial plasma arcs.



MITIGATION STRATEGIES (1)

- **Bring the conductor potential up to near plasma potential:**
  - **use a plasma contactor, or**
  - **increase exposed ram conductor area (LEO), or**
  - **increase secondary electron emission (GEO).**
- **Coat insulators with conductor, and ground them to conductor potential:**
  - **ITO or other very conductive material.**
  - **Conductivity of LEO coatings must be greater than for GEO coatings.**
  - **Total LEO parasitic current will be greatly increased.**



MITIGATION STRATEGIES (2)

- **Prevent Paschen discharges from occurring:**
  - **use low outgassing materials, and**
  - **prevent inadvertent gas flows, or**
  - **use only voltages lower than the Paschen discharge minimum.**
- **Prevent adjacent solar cells or conductors from arcing across a gap:**
  - **use intelligent string layouts (serpentine, leapfrogged, or all in same direction) so adjacent cells don't have large potential differences, or**
  - **place a physical barrier to arc currents between cells (grout between cells, or separate cells by several millimeters), or**
  - **limit string currents and/or voltages to below the continuous arc thresholds.**